Abstract—A method is proposed to estimate the direction of a ground radio-frequency (RF) transmitter by using an Unmanned Aerial Vehicle (UAV) equipped with a single antenna, which is critical when considering the form factor and computational capabilities of a UAV. By considering the received signal at several locations along its trajectory, the UAV receiver implicitly creates a virtual multi-antenna array (VMA), which can estimate the direction-of-arrival (DOA) of the transmitter. The major difficulty is the Local Oscillator (LO) frequency offset that occurs between the transmitter and the UAV receiver, which adds a cumulative phase offset to the received signal at each antenna of the virtual array. Oscillators of inferior qualities will undergo severe phase and frequency drifts over time, and these LO offsets must be estimated and compensated during DOA estimation. To overcome this difficulty, we proposed two approaches by estimating the LO frequency offset jointly with the direction of the transmitter. Then we extend the Multiple Signal Classification (MUSIC) algorithm to perform multidimensional estimation (including azimuth and elevation). In this paper, the proposed VMA method is simulated and tested by considering different virtual array geometries and various LO qualities. Simulation results prove the feasibility of our proposed method, and the median estimation error for azimuth and elevation are below $9^\circ$ and $12^\circ$ on average, even with low-quality oscillators.

Index Terms—Direction of arrival, Flying base stations, MUSIC, Ray-tracing, RF localization, UAV, Virtual antenna array

I. INTRODUCTION

Using Unmanned Air Vehicles (UAVs) for military and civilian applications has been steadily increasing in recent years. One potential application of UAVs is to use them as “flying base stations”, allowing to extend the coverage and capacity of existing wireless networks. Such UAV-based networks are interesting for extending the range of a network, serving remote areas, or temporarily replacing cellular infrastructure in disaster scenarios (e.g. flood, hurricane, etc.) [1]. One critical aspect of UAV networks is to determine the optimal location for each UAV, which can be challenging if the location of the ground users is unknown or if the ground users are non-cooperative. The global positioning systems (GPS) has been applied in many outdoor scenarios to capture the ground user’s position, and it provides satisfactory performance. However, GPS requires the user to broadcast its location, which might not always be possible. It is also known for its high cost and vulnerability to jamming, especially in dense urban environments. Therefore, alternative RF source localization techniques in UAV-based networks have attracted considerable focus recently.

One possible method for determining the location of the ground RF transmitter is by estimating its bearing with respect to multiple access points [2]. For example, the multi-antenna method has already proven to be an efficient way for estimating the Direction-of-Arrival (DOA) of an RF transmitter in [3]. The major disadvantages of multi-antenna arrays are the high cost and enormous form factors associated with such arrays, making them unsuitable for UAV-based networks. Compared with our previous research [4], we investigate the feasibility of DOA estimation with a UAV equipped with a single, omnidirectional antenna. By considering the successive received signal packets at different positions along the UAV’s trajectory, the UAV receiver implicitly creates a virtual multi-antenna array, which can be used to estimate the DOA (for both azimuth and elevation angles) of the RF transmitter, as shown in Fig. 1. The major difficulty is that the cumulative phase because of the Local Oscillator (LO) frequency offset needs to be removed for DOA estimation. The significance of our work lies in proving the feasibility of such a DOA estimation method with cheap, portable hardware that is already available in modern smartphones. This method is especially suitable for UAV-based networks since it does not increase energy consumption or requires additional hardware modifications on the UAV.

Related work: Most works on UAV-based networks have investigated various design challenges that include network characterization, performance improvement, 3D deployment of UAVs and user-to-UAV association. For instance, the work in [1] has made an excellent summary on UAV communication network design, by addressing its major challenges and new contributions. Regarding RF source localization with UAVs, the major challenge has always been the uncertainty that plagued the localization metrics, mostly due to multipath fading. A variety of signal parameters can be used for localizing RF transmitters. In [5], the localization of an RF transmitter is considered via a group of UAVs equipped with omnidirectional Received Signal Strength (RSS) sensors. This RSS-based method suffers heavily from multipath propagation and shadowing effects. In [6], the researchers have proposed
We propose a system to estimate the direction of a ground RF transmitter using a UAV equipped with a single omnidirectional antenna. The system proposes practical, realistic solutions to account for the hardware requirements of UAV-based networks.

We propose two new methods to evaluate the LO frequency offset between ground RF transmitters and UAV receivers, further building on our previous work.

We evaluate the performance of our virtual multi-antenna array DOA estimation method in line-of-sight (LoS) scenarios by considering different virtual array geometries and various LO qualities.

II. DOA ESTIMATION SYSTEM DESIGN

A. UAV Virtual Multi-antenna Array Configuration

DOA estimation algorithms rely on analyzing the phase differences between the multiple antenna elements at the receiver. Therefore, our system model will include non-idealities that affect the phase of received signal at each UAV “virtual” antenna element. Typically, two non-idealities will cause phase distortions: 1) the ground RF transmitter and the UAV receiver front-end phase offset; and 2) the frequency offset between the ground RF transmitter and the UAV receiver. We ignore the effect of LO phase noise; its influence on the proposed method is also negligible.

We consider a transmitter sending an RF signal in the form of digital data packets. The preamble of the packets is defined by the communication standard (e.g., the primary synchronization sequence in 3G systems or the short/long preamble in 802.11 systems). Both the transmitter and the receiver know the preamble of the packets. The packets sent by the transmitter may or may not be periodic. The receiver correlates its received baseband samples with the known preamble to determine the boundaries of the received packets.

Let us denote \( s[m] \) the baseband representation of the transmitted packet header (for \( m = 1, ..., M \)) and \( r[n,m] \) the \( m \)-th baseband sample of the \( n \)-th received packet, which can be represented as:

\[
    r[n,m] = h[n,m] * s[m] \cdot e^{j(\phi_0 + 2\pi f_0 (t_n + mT_s))} + \omega[n,m]
\]

where \( h[n,m] \) is the wireless channel impulse response (CIR) and including multipath components. The term \( \phi_0 \) is the phase of the first received packet (which contains the phase offset and accumulated frequency offset at time \( t_0 \)) between the transmitter and receiver front-ends; \( f_0 \) is the frequency offset between the transmitter and receiver due to LO frequency offset; \( t_n \) is the elapsed time between the initial packet and the \( n \)-th packet. The term \( T_s \) indicates the receiver sample time and \( \omega[n,m] \) is an independent and identically distributed Gaussian noise with distribution \( \omega[n,m] \sim CN(0, \sigma^2) \). Note that (1) implicitly assumes that the frequency offset \( f_0 \) does not change over time, which is basically true for short periods of time, e.g., a few seconds for a temperature-controlled crystal oscillator (TCXO), a few tens of seconds for an oven-controlled crystal oscillator (OCXO). If the transmitter up-conversion chain and

![Virtual array estimation concept. Single UAV receiver equipped with one single antenna, moves and create a virtual array. We estimate the DOA of the ground transmitter by considering the successive received signal packets at each UAV positions.](Image)

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the receiver down-conversion chain (both analog and digital) are not turned off between the considered packets (which is the case for most modern transceivers), the term $\phi_0$ will remain constant between multiple received packets.

B. Channel Simulations for CIR

Without loss of generality, we use ray-tracing method to generate realistic CIRs and test the performance of our DOA estimation method for UAV virtual arrays. The ray-tracing simulations can generate CIRs based on a wide range of multipath channel parameters, including time delays and propagation angles for multipath components. To simulate the $h[n,m]$ in (1), we construct a subcity model as the communication scenario, as shown in Fig. 2. Our simulations are conducted by using CloudRT, a high-performance-computing software developed by Beijing Jiaotong University [12]. We have simulated the snapshots between UAV virtual arrays (at the center of the 3D map with an altitude of 80m) and 5,000 uniformly distributed ground transmitters (all have LoS visibility). Considering that Long-Term Evolution (LTE) is a reliable technology to support required link performance of UAV networks, we set the carrier frequency at 2.6 GHz, corresponding to LTE carrier frequencies [7]. Fig. 2 also displays one snapshot from our ray-tracing simulations. We consider the UAV is equipped with a downward-facing patch antenna, and ground transmitters are equipped with vertically oriented dipole antennas. In this section, both UAV receivers and ground RF transmitters are equipped with a high-accuracy OCXO local oscillator, while the performances of different local oscillators are analyzed in Section III.

For example, in a narrowband LoS channel, $h[n,m]$ is defined as

$$h[n,m] = \alpha_0 \cdot e^{j\vec{\beta} \cdot \vec{r}[n]} + \sum_{k=1}^{N_{n,m}} G_{t_k} \cdot \alpha_k e^{j(\phi_k + \vec{\beta}_k \cdot \vec{r}[n])} \cdot G_{r_x}$$

where the LoS component to the transmitter has an amplitude of $\alpha_0$, and $(G_{t_k}, G_{r_x})$ denote the polarimetric $T_x$ and $R_x$ antenna radiation patterns. The term $\alpha_k$ is the relative amplitude of ray $k$, $\phi_k$ is the phase of ray $k$ and $\vec{\beta}_k$ is the wave vector (containing DOA information); $\vec{r}[n]$ are the relative coordinates of the receiver when the UAV receives the $n$-th packet and therefore depend on the movement of the UAV receiver, which is different compared with the conventional multi-antenna arrays where the positions of the antennas are fixed. While the UAV flies following planned trajectory, it implicitly creates a virtual uniform array, and the term $\vec{\beta} \cdot \vec{r}[n]$ can then be developed as follows [4]:

$$\vec{\beta} \cdot \vec{r}[n] = \frac{2\pi}{\lambda} \left( x[n] \sin(\varphi) \cos(\theta) + y[n] \cos(\varphi) \sin(\theta) + z[n] \cos(\theta) \right)$$

Where $\varphi$, $\theta$ is the azimuth-of-arrival and the elevation-of-arrival from the transmitter, respectively. The term $\lambda$ is the wavelength w.r.t the carrier frequency, and $x[n]$, $y[n]$, $z[n]$ are the $x$-, $y$- and $z$- coordinates of the UAV receiver when receiving the $n$-th packets.

![Fig. 2. One example snapshot from ray-tracing simulations. The transmitters are randomly distributed on the ground, and the UAV receiver is flying at 80m. The total length of the trajectory is 6m and each elements are separated by half a wavelength (7cm). The solid red line represents the line-of-sight path between the UAV virtual array and a ground RF transmitter. The blue lines represent all the multipath components, including reflected rays, scattered rays and diffracted rays.](image)

Our target is to leverage DOA estimation techniques that are already available for conventional multi-antenna arrays. Combine (1), (2) and (3) (we ignore multipath components for simplicity in the following description), we have

$$r[n,m] = \alpha_0 \cdot s[m] \cdot e^{j(\phi_0 + 2\pi f_0(t_n + mT_s) + \vec{\beta} \cdot \vec{r}[n])} + \omega[n,m]$$

(4)

The primary difference between (4) and the signal at each antenna in a conventional multi-antenna array is the term $2\pi f_0T_s$. This frequency offset $f_0$ needs to be estimated and compensated in the received signal. After that, the DOA can then be estimated applying traditional multi-antenna array processing techniques, such as MUSIC, beamforming and Estimation of Signal Parameters via Rotational Invariance Technique (ESPRIT) [13].

C. LO Frequency Offset Compensation

To estimate and compensate the LO frequency offset in (4), we proposed two methods, based on our previous research in [11]. The first method is a Stop-and-Start (SaS) approach, where the UAV receiver first stands still before starting to move. During standstill, only the LO frequency offset causes the phase to change in (4), and can easily be estimated. This estimated value $f_0$ is then used during the movement of the UAV receiver to compensate the LO frequency offset, where each subsequent packet received by the UAV receiver during its moving in (4) can be compensated as follows:

$$r'[n,m] = r[n,m] e^{-j2\pi f_0T_s}$$

(5)

The phase of the compensated packet should only change due to the movement of the UAV receiver. The complex signal $r'[n,m]$ can then estimate the DOA by applying conventional methods, e.g. 2D MUSIC.

In this section, The LO drift is simulated using the LO model described in [14], [15], with the parameters $q_1^2 = 5.25 \cdot 10^{-24}$ and $q_2^2 = 1.77 \cdot 10^{-21}$, which are the values for
OCXOs. Fig. 3 shows the effects of the SaS method. In our simulation configuration, we consider that the UAV receiver first remains at standstill for 1 second, then moves following the pre-defined trajectory for 2 seconds. As illustrated in Fig. 3(a), we use the packets received in the last 0.2s before the UAV starts moving to estimate the LO frequency offset $f_0$. Fig. 3(b) shows the phase of the received packet before frequency offset compensation. The phase variations before the movement ($0 \sim 1s$) are mostly due to the local oscillator drift between the transmitter and the receiver. Therefore, the phase shift due to the UAV movement cannot be identified. However, after compensating for the frequency offset, the phase shift due to the movement can be clearly observed, as shown in Fig. 3(c).

$$y[m] = a(f_0, \varphi, \theta) \cdot x[m] + \omega[m]$$  \hspace{1cm} (6)

where $a(f_0, \alpha, \theta)$ represents the steering vector (containing the LO frequency offset) defined as

$$a(f_0, \alpha, \theta) = \begin{bmatrix} e^{j(2\pi f_0 t_1 + \beta x[1])} \\ e^{j(2\pi f_0 t_1 + \beta y[2])} \\ \vdots \\ e^{j(2\pi f_0 t_1 + \beta x[N])} \end{bmatrix}$$  \hspace{1cm} (7)

and $x[m]$ contains the constant terms for all virtual antenna elements, defined as

$$x[m] = \alpha_0 \cdot s[m] \cdot e^{j(\phi_0 + 2\pi f_0 m t_s)}$$  \hspace{1cm} (8)

and $\omega[m]$ is the $N \times 1$ white Gaussian noise vector, with covariance matrix $R_n = \sigma_n^2 I_N$, where $\sigma_n^2$ and $I_N$ represent the noise power and unit matrix, respectively.

We can use the adapted signal model (6) with the MUSIC algorithm. Let us define $S = E\{yy^*\}$ as the $N \times N$ covariance matrix, where $E\{\cdot\}$ and $(\cdot)^*$ are the expectation and the Hermitian operator, respectively. By developing the eigen-decomposition of $S$, we obtain noise subspace $E_\omega$. Then the MUSIC algorithm estimates the direction of the RF source by performing a spectrum search as follows:

$$P_{MU}(f_0, \varphi, \theta) = \frac{1}{a^*(f_0, \varphi, \theta) E_\omega E_\omega^* \cdot a(f_0, \varphi, \theta)}$$  \hspace{1cm} (9)

Similarly to the beamforming case, $f_0$, $\varphi$ and $\theta$ thus can be estimated simultaneously with a three-dimensional search:

$$\left(\hat{f}_0, \hat{\varphi}, \hat{\theta}\right) = \arg \max_{(f_0, \varphi, \theta)} \{P_{MU}(f_0, \varphi, \theta)\}$$  \hspace{1cm} (10)

Note that in the case of multipath channels, the MUSIC algorithm offers a much better resolution in spectrum searching than simple beamforming [11].

D. UAV Receiver DOA estimation

In the following step, we will illustrate the spectrum searching result of our proposed virtual array method with two LO frequency offset compensation techniques, respectively.

![Fig. 4. Simulation results of the SaS estimation approach based on 2D MUSIC search.](image)

(a) Azimuth estimation for SaS

(b) Elevation estimation for SaS

Fig. 4 shows the MUSIC spectrum of the SaS method after frequency offset compensation, which is used to estimate the azimuth and elevation angle simultaneously. In this snapshot, a clear peak is observed at azimuth 8° and elevation 56°, which is very close to the true DOA (12° for azimuth and 52° for elevation).
Fig. 5 presents the results of the joint-estimation method for the same snapshot in Fig. 4. In this case, only the received packets during the UAV movement were used for processing. The peak of the spectrum indicates the estimated LO frequency offset $f_0$, and also the estimated DOA (azimuth and elevation) corresponding to the peak. A clear peak can be identified at $10^\circ$ for azimuth and $55^\circ$ for elevation, close to the true DOA of $12^\circ$ for azimuth and $52^\circ$ for elevation as well.

### III. UAV Virtual Array Performance Evaluation

In this section, we evaluate the performance of our UAV virtual multi-antenna array DOA estimation method based on a large amount of simulation results, by also considering the LO offset compensation approaches, LO qualities and UAV movement trajectories. To achieve these goals, we perform the DOA estimation for all 5,000 transmitters, similar to Fig. 2, under each system configuration. The comparison between different parameters and their effects on estimation accuracy are discussed in following.

#### A. Virtual array performance vs Compensation method

Two LO frequency offset estimation and compensation techniques are investigated for our DOA estimation method of ground RF transmitters. The first method is the SaS approach, where the UAV receiver remains at standstill before moving. The second method is the joint-estimation algorithm by applying an adapted signal model. Fig. 6 shows that the estimation results for both the SAS approach and the joint-estimation approach are pretty good (despite the presence of multipath in the simulation). It can be seen that in LoS scenarios, the median estimation errors are below $7^\circ$ and the maximum estimation errors are below $15^\circ$ for both azimuth and elevation angles, showing that LO offset can effectively be compensated and the effects of multipath are minor. The advantage of the joint-estimation method is that there is no need to stop the UAV receiver before the movement. Such usage flexibility comes at the cost of more computation power to perform the three-dimensional search over $f_0$, $\varphi$, and $\theta$. The SaS approach estimates the LO frequency offset at standstill, which is easy, but the true LO frequency offset might drift between the standstill and the movement phase.

#### B. Virtual array performance vs Local oscillator qualities

Although the results in Section III-A seem encouraging, the above setup w.r.t local oscillators is quite idealized compared to realistic scenarios. In modern portable equipment industry, low-quality oscillators are more common, such as TCXO, due to their cheap cost and low power consumption while providing relatively high stability. However, the phase and frequency drifts caused by them may be too severe to satisfy the limits in our LO offset compensation methods. Therefore, we evaluate the estimation performance by considering different transceivers setups. For easy comparison, median values of estimation errors (the same with Fig. 6) in different LO configurations are listed together in Table 1.

<table>
<thead>
<tr>
<th>Setup 1</th>
<th>AOA</th>
<th>EOA</th>
<th>AOA</th>
<th>EOA</th>
</tr>
</thead>
<tbody>
<tr>
<td>SaS</td>
<td>1.29°</td>
<td>6.22°</td>
<td>3.42°</td>
<td>9.31°</td>
</tr>
<tr>
<td>Joint</td>
<td>1.37°</td>
<td>6.17°</td>
<td>4.72°</td>
<td>8.54°</td>
</tr>
<tr>
<td>Arc Trajectory</td>
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<td>6.50°</td>
<td>3.34°</td>
<td>6.80°</td>
</tr>
<tr>
<td>SaS</td>
<td>2.40°</td>
<td>6.91°</td>
<td>4.70°</td>
<td>8.63°</td>
</tr>
<tr>
<td>Joint</td>
<td>6.17°</td>
<td>8.46°</td>
<td>4.65°</td>
<td>7.99°</td>
</tr>
<tr>
<td>Arc Trajectory</td>
<td>9.17°</td>
<td>10.41°</td>
<td>10.41°</td>
<td>10.41°</td>
</tr>
</tbody>
</table>

1. Setup 1: OCXO for both transmitter and receiver;
2. Setup 2: TCXO for transmitter and OCXO for receiver, which is the most common case;
3. Setup 3: TCXO for both transmitter and receiver;

As we can see, the median estimation error of the virtual array with SaS method and joint-estimation are both lower than $10^\circ$, even the ground transmitters are equipped with low-quality TCXO oscillators. This result shows that the UAV virtual array DOA estimation method can be feasible with cheap, off-the-shelf hardware, which typically has significant LO frequency offset.
C. Feasibility of different UAV trajectories

In our previous work, we consider that the UAV flies in a circle, as shown in Fig. 7(a), and thus creates a uniform circle array, which already been widely used in conventional DoA methods. However, in real life, it is idealized to make the UAV moves in a perfect circle which would also deviate from UAV’s original mission planning. Therefore, we test the feasibility of the virtual DOA estimation by considering more realistic UAV trajectories. We take one example and presented in Fig. 7(b).

![UAV Trajectories](image)

Fig. 7. UAV virtual array design under different UAV trajectories.

The estimation errors of the new arc trajectory are summarized in Table 1. As we can see, there is no significant degrade for the designed realistic trajectory compared with the ideal uniform circle trajectory. This results show that the proposed virtual array method is also applicable for customised UAV trajectories with known configurations and steering vectors. The major difficulty lies in the positions of the UAV receiver needs to be estimated with an accuracy of a fraction of a wavelength. In this paper, we assume that we know the perfect position of the UAV receiver. It can be argued that new generations of GNSS receivers will allow to know the position of the UAV with high accuracy, especially since UAVs benefit from excellent satellite visibility. In addition, while these errors can be considered high with respect to conventional multi-antenna arrays, it needs to be reminded that this is a fundamental shift from conventional multi-antenna DOA estimation theory. We are trying to estimate DOA with a UAV that equipped a single antenna receiver, which requires estimating and compensate LO frequency offset. In that respect, it can be expected that performances would decrease. We believe that further optimisation of the LO offset/DOA estimation methods in UAV-based networks is possible, and better design of UAV receiver trajectories to compose virtual multi-antenna array can be performed to improve DOA estimation performances and save computation power. However, this is beyond the scope of this paper.

IV. CONCLUSION

A promising method is proposed to estimate the DOA of a ground RF transmitter with a UAV that equipped with a single antenna. This method actively exploit the UAV movement, which can effectively be controlled and leveraged to obtain DOA estimations. By considering received packets along planned trajectory, the UAV receiver creates a virtual multi-antenna array that can use conventional DOA estimation algorithms. In addition, we propose two alternative methods to compensate for the local oscillator frequency offset between ground RF transmitters and UAV receivers. We test the estimation accuracy by considering many realistic parameters, including channel conditions, LO qualities and UAV trajectories. The estimated DOAs of ground users after LO frequency offset compensation is calculated and compared with the true DOAs, and the feasibility of our UAV virtual array method are thus verified. Our future work will focus on evaluating and improving the robustness of the proposed method and tested on our hardware testbed.

REFERENCES